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Stability analysis of an open pit by numerical modelling

The stability of a copper open pit slope was investigated by analyzing two dimensional finite difference models of the pit slopes. The result was found to be in agreement with the findings of limit equilibrium method. In the course of the study, geotechnical mapping was done to determine the critical orientation of geological discontinuities. Geotechnical properties were determined in the laboratory. The analysis by numerical modelling and limit equilibrium method of the open pit slopes indicate that 148 m deep open pit is stable with 60° overall slope angle.

Introduction

This paper discusses the stability analysis and slope design of a copper open pit situated in Rajasthan, with the help of a two dimensional microcomputer programme, FLAC (Fast Lagrangian Analysis of Continua). The results obtained by FLAC was also checked by limit equilibrium method of analysis.

FLAC is an explicit finite difference code to simulate the behaviour of soil and rock slopes which may undergo plastic flow when their yield limit is reached. Finite difference technique is a complex computer technique for modelling a slope using small computerized geometric elements to which various material properties can be assigned. This method is capable of analyzing the deformation and safety by computing the stresses and strains, of the slope (Cundall [1], Cundall and Board [2]). FLAC is particularly useful because it enables displacement to be modelled with time as excavation proceeds (Plessis and Martin [3]).

The open pit is 500 m long and 200 m wide, strike length of the orebody being 313 m and depth 148 m (496 m R. L.-348 m R. L.). The major mineral is chalcopyrite. The orebody dips at a steep angle of about 60° with average true width of about 30 m. Total minable reserve is 2.25 million tonnes of an average grade of 1.274 %.

Since the orebody is relatively small and steeply dipping, the profitability of the mine is largely dependent on the steepest possible final slope angle. Earlier (before this geotechnical study) the open pit was designed at 45° overall slope angle. Therefore, the study for an optimum slope design of the open pit was sought by the mine management. The study included detailed geotechnical mapping of the discontinuities, determination of geomechanical properties of the slope material and finally stability analysis using an explicit finite difference code, FLAC and limit equilibrium method, both. The various parameters thus considered for this analysis are discussed below.

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Geological investigation

Geotechnical mapping was done in and around the partially developed open pit. The amphibole felspathic quartzite (AFQ) is mainly exposed towards the hanging wall side. Mineralization is limited to amphibole felspathic quartzite. Felspathic quartzite (FQ) is mainly exposed towards the footwall side. A dyke dipping at 80° towards hanging wall is also present in the middle part of the pit (Fig. 1).

The statistical analysis of the orientation data was done with the help of SNAP computer program (Jeran and Mashy[4]). A few necessary modifications were made in the programme according to the requirements and the computer compatibility. It uses the lower hemisphere of polar equal area projection. SNAP was used to prepare density plot (Fig. 2) to delineate different joint sets present in the rock mass of the pit slope. SNAP uses one per cent area of circle to make density plot. The mean and range of joint sets orientation from total 719 observation data are presented in Table 1.

TABLE 1 - MEAN ORIENTATION OF JOINT SETS

Joint set	Mean orientation of joint sets	
	Dip direction (degree)	Dip amount (degree)
J1	N011±7	82±3
J2	N338±7	82±5
J3	N100±10	81±5
J4	N219±18	24±8
J5	N273±8	81±6

SPACING

The joints are having "Moderate spacing" (between 20 to 60 cm) to "Wide spacing" (ISRM [5]), i.e. between 60 to 200 cm. As such the rock mass is massive bedded. The spacing of the bedding plane is greater than three meters. Wide spacing can also be attributed by the high value of RQD of the rocks which is about 80%.

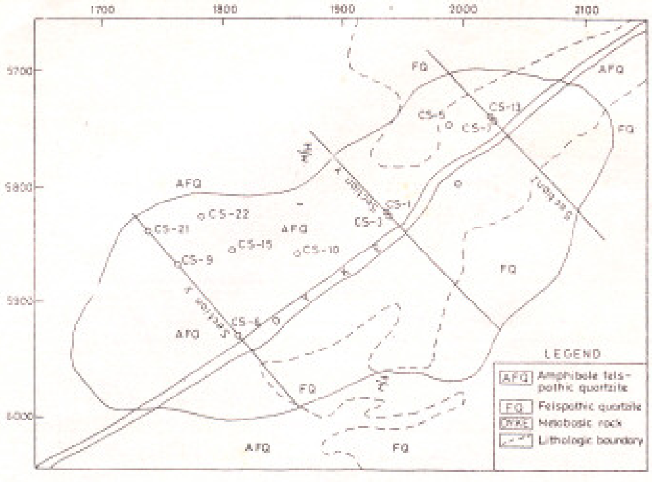

Fig.1. Geological map of the copper open pit

KEY TO SYMBOLS USED -

SYMBOL	ACTUAL COUNT	PERCENTAGES
1	1 - 11	.00 - 1.54
2	12 - 22	1.54 - 3.09
3	23 - 33	3.09 - 4.63
4	34 - 44	4.63 - 6.18
5	45 - 55	6.18 - 7.72
6	56 - 66	7.72 - 9.26
7	67 - 77	9.26 - 10.81
8	78 - 88	10.81 - 12.35
9	89 - 99	12.35 - 13.89
A	100 - 111	13.89 - 15.44
B	112 - 122	15.44 - 16.98

Fig.2. Density plot of orientation data of the discontinuities by SNAP

PERSISTENCE

J1 and J2 are systematic joint sets. J3 and J4 are sub-systematic joint sets. J5 is non-systematic joint set (ISRM[5]). As such the persistence of J1, J2 and J3 joint sets was traced to be 20 m in their dip direction, which is of high persistence (ISRM [5]).

ROUGHNESS

Attempts were made to measure the roughness precisely. Although only a few discontinuities could be found suitable for roughness measurement due to inaccessibility of large exposed discontinuity surface. The dip direction and dip amount were obtained with the help of Clar compass by putting 5, 10, 20 and 40 cm dia circular discs at various positions over a few discontinuity surfaces. The effective large scale roughness angle, estimated from 40 cm circular disc, in the direction of potential sliding for the joints of amphibole felspathic quartzite and felspathic quartzite is 3°. The joints are smooth planar.

APERTURE

Most of the joints (about 90%) were found to be closed type. Few open fractures were noticed in the slope which seems to be induced fractures developed by poor blasting.

FILLING MATERIAL

Practically there was no filling material because most of the joints are of closed type. However, a few joint apertures are filled with siliceous material mainly derived by the weathering of the adjacent parent rock.

Ground water

The rocks of the copper open pit are well jointed with moderate spacing. The mine is located is semi arid region of India, where rainfall is only about 50 cm/year. Except in rainy season the pit remains dry. Suitable surface drains were also provided to divert the rain water away from the pit. These surface drains are properly maintained, especially in rainy season, to keep them effective. So, the slope was regarded as drained.

Geomechanical properties

ROCK QUALITY DESIGNATION (RQD)

The RQD of amphibole felspathic quartzite and felspathic quartzite was found to be 80% during core logging of borehole nos. CS1, CS5, to CS7, CS10, CS11, CS13 and CS22 (Fig. 1). However, the top 20 m weathered and jointed mass is characterized by about 30% RQD.

SHEAR STRENGTH PARAMETERS

Coulson[6], Hoek and Londe[7], Hoek and Bray[8], McMahon[9] and Bandis[10] inferred that the problem of scale effect, during testing the samples in the laboratory, can be resolved by determining the residual friction angle values in the laboratory. Further the large scale roughness angle is added to the residual friction angle value to estimate the shear strength of the joint surface. So it was decided to use saw cut samples to determine the residual friction angle in the laboratory. The large scale roughness angles of the joint surfaces were added to the residual friction angles of the saw cut samples to get the realistic friction angle values (Table 2). These values were cross checked by back analysis of two failed slopes of bench scale in the mine. The effective cohesion mobilised during the failure was estimated by back analysis of the same failed slopes, which is 0.5 MPa for 33° friction angle for joints in felspathic quartzite and 0.48 MPa for 35° friction angle for joints in amphibole felspathic quartzite. These values are used for the stability analysis of the slopes with J1, J2, J3, and J5 joint sets.

The friction angle for J4 joint set and bedding plane of amphibole felspathic quartzite and felspathic quartzite was selected to be 32° and 30° respectively, i.e. the residual friction angle, because of their remarkable planarity. The cohesion for the bedding plane and J4 joint set (striking parallel to bedding plane) was assumed to be zero due their greater persistence along dip direction.

TABLE 2 - REALISTIC VALUES OF FRICTION ANGLES

Rock type	Laboratory determined friction angle (φr) of saw cut samples (mean) (degree)	Large scale mean field roughness angle (i) (degree)	Realistic value of friction angle (φr+i) (mean) (degree)
Amphibole felspathic quartzite	32	3	35
Felspathic quartzite	30	3	33

TRIAXIAL COMPRESSION TEST

The tested specimens of AFQ and FQ are characterized by Mohr envelopes with a slope of 56° and 53° along with cohesion intercept of 127.5 MPa and 147.15 MPa respectively.

DETERMINATION OF DEFORMATION CONSTANTS

Poisson's ratio (v) and modulus of deformation (E) was obtained from laboratory testing of the rock material. These test values were used to select the rock mass properties based on acceptable empirical criteria (Plessis and Martin[3]). A suitable reduction factor can also be used to get in-situ properties from intact rock sample properties (Sharma et al.[11]).

The Geomechanics classification (Bieniawski [12]) was used to estimate the rock mass rating (RMR) of the rock mass. The in situ modulus of deformation (E_{rm}) was estimated (Table 3) from RMR using the relationship proposed by (Bieniawski[13]). He has proposed the following equation for rocks with RQD greater than 50%.

TABLE 3 - CONVERSION OF LABORATORY TESTED VALUES TO E_{rm} VALUES

Rock type	RQD %	RMR	Lab. tested values of E ($x10^4$ MPa)	E_{rm} ($x10^4$MPa
AFQ	80	60	38	20
FQ	80	60	35	20

$$E_{rm} = 2xRMR - 100 \quad (1)$$

According to him the equation is sufficiently accurate for practical engineering purposes.

The other deformation constants used for modelling are listed in Table 4. The bulk moduls (K) and shear modulus (G) were estimated from E_{rm} using the following accepted formulae

$$K = E_{rm} / \{3x\ (1-2v)\} \quad (2)$$

$$G = E_{rm} / \{2x\ (1+V)\} \quad (3)$$

TABLE 4 - DEFORMATION CONSTANTS FOR THE COPPER OPEN PIT ROCKS

Rock type	E_{rm} ($x10^4$ MPa)	Poisson's ratio	Bulk modulus ($x10^3$MPa)	Shear modulus ($x10^3$MPa)
Amphibole felspathic quartzite	20	0.15	9.5	8.69
Felspathic quartzite	20	0.13	9.0	8.69

Stability analysis

A numerical modelling study was done to assess the stability of steepening the final slope. Modelling was conducted using the FLAC microcomputer programme marketed by Itasca Consulting Group Inc.[14]. It is a two dimensional programme. It can be modelled on a standard 640 k personal computer and grids up to 2000 elements.

To obtain information on the mechanism of a slope slide, an ubiquitous joint model was used to all the zones during the case study, because of jointed rock condition at the mine site. The ubiquitous joint model is an anisotropic plasticity model which assumes a series of weak planes embedded in a Mohr-coulomb solid. Yield may occur in either the solid or along the weak plane, or both, depending on the geomechanical properties of the rock and weak planes.

The essential geotechnical properties needed for the analysis are summarized in Table 5. Tensile strength along joints was assumed to be 0.01 MPa from the engineering judgment.

The critical discontinuity dips within ±20° dip and dip direction of the slope face for plane failure condition. The

TABLE 5 - GEOMECHANICAL PROPERTIES FOR NUMERICAL MODELLING

Properties	Hangingwall	Footwall
Shear modulus (MPa)	$8.69x10^3$	$8.85x10^3$
Bulk modulus (MPa)	$9.50x10^3$	$9.00x10^3$
Density (kN/m^3)	26.28	25.69
Cohesion of rock (MPa)	1.3	1.5
Friction of rock (degree)	56	53
Cohesion of joint (MPa)	0.049	0.051
Joint friction angle (degree)	35	33
Joint tensile strength (MPa)	0.01	0.01

mean dip direction of J1 joint set is NO 11° (Table 1), which is oblique to the dip direction (NO 30°) of hanging wall slope face (Fig.3). But a few joints of J1 joint set which has dip direction within ±20° of the hanging wall slope face, i.e. between NO10° to NO50°, shall daylight in the slope face of hangingwall and may become critical for plane failure condition. Hence, it was decided to use the orientation data between ±20° of slope face dip direction during slope design, So, the orientation data between dip direction NO10° to NO50° (within ±20° of the slope face) were selectively retrieved from the total 719 orientation data. Only 172 joints had dip direction between NO10° to NO50°. Further, SNAP computer programme is used for dip ring analysis (Table 6) of these data to know how many joints are dipping at an angle greater than 35° (i.e. friction angle of AFQ in the hangingwall slope), which will daylight in the slope and may cause unsafe conditions.

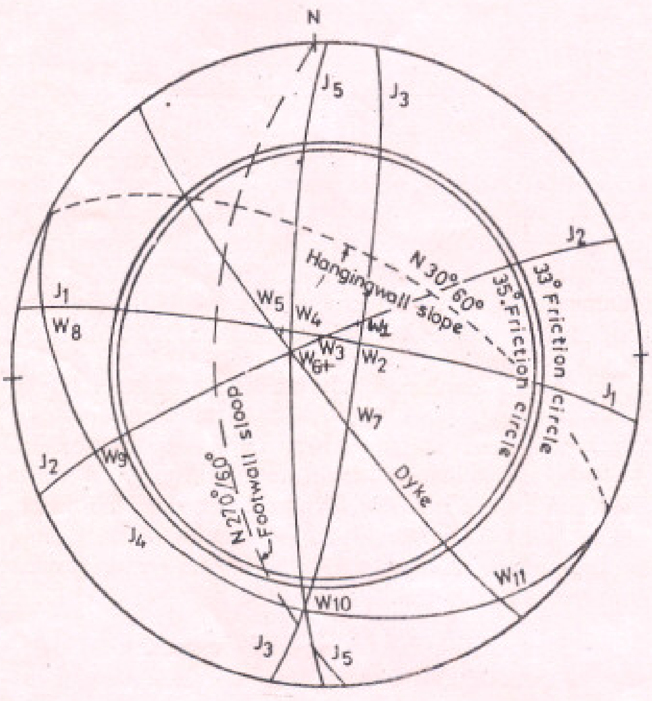

Fig.3. Stereoplot showing kinematics analysis for types of failure

It is evident from Table 6 that the joints are distributed between 46° to 90° dip. But less than 5%, of 172 joints, are occurring in each dip ring from 45 to 60°. However, a sharp increase in the percentage of daylighting joints (>9 %) can be noticed from dip range 60° - 65° (Table 6). These are having approximately same strike/ dip direction as that of the hanging wall slope face. So, by selecting the slope angle more than 60°, greater number of critical joints will daylight in the slope face. The main idea behind overall slope design is to take minimum risk. Hence, a minimum number of potential failure plane are allowed to daylight.

From stability analysis it was seen that joints dipping at an angle less than 56° are stable in 65° hanging wall slope face. So, modelling with joint dip less than 56° was not necessary. Further modelling for joints dipping at an angle greater than 60°/65° was also useless because these will not daylight in the 60°/65° slope. So, it was decided to do modelling with 58° joint dip (the most critical joint orientation) for 60° and 65° overall slope angle for hangingwall side.

The kinematic analysis for types of failure of footwall slope shows that J5 is the only critical joint set (Fig.3).The dip ring analysis (Table 7) was done, by SNAP computer pro-

TABLE 6 - DIP RING ANALYSIS FOR HANGINGWALL SLOPE
(18 rings of 5.0 degree each)
(172 observations)

Sr. No.	Range (degree)	Number	Per cent
1	0.0 - 5.0	0	0.0
2	5.0 - 10.0	0	0.0
3	10.0 - 15.0	0	0.0
4	15.0 - 20.0	0	0.0
5	20.0- 25.0	0	0.0
6	25.0 - 30.0	0	0.0
7	30.0 - 35.0	0	0.0
8	35.0 - 40.0	0	0.0
9	40.0 - 45.0	0	0.0
10	45.0 - 50.0	5	2.9
11	50.0 - 55.0	4	2.3
12	55.0 - 60.0	6	3.5
13	60.0 - 65.0	16	9.3
14	65.0 - 70.0	14	8.1
15	70.0 - 75.0	14	8.1
16	75.0 - 80.0	36	20.9
17	80.0 - 85.0	57	33.1
18	85.0 - 90.0	20	11.6

TABLE 7 - DIP RING ANALYSIS FOR FOOTWALL SLOPE

(18 rings of 5.0 degree each)
(75 observation)

Sr.No.	Range (degree)	Number	Per cent
1	0.0 - 5.0	0	0.0
2	5.0 - 10.0	0	0.0
3	10.0 - 15.0	0	0.0
4	15.0 - 20.0	0	0.0
5	20.0 - 25.0	1	1.3
6	25.0 - 30.0	0	0.0
7	30.0 - 35.0	0	0.0
8	35.0 - 40.0	0	0.0
9	40.0 - 45.0	0	0.0
10	45.0 - 50.0	0	0.0
11	50.0 - 55.0	0	0.0
12	55.0 - 60.0	4	5.3
13	60.0 - 65.0	7	9.3
14	65.0 - 70.0	6	8.0
15	70.0 - 75.0	8	10.7
16	75.0 - 80.0	13	17.3
17	80.0 - 85.0	30	40.0
18	85.0 - 90.0	6	8.0

gramme for the joints of J5 joint set which has dip direction within $\pm 20^{o}$ dip direction of the footwall slope. It shows that only one joint is found to be dipping at less than 55^{o} dip. However, about 5% joints are having dip between 55^{o} and 60^{o}. Hence, it was decided to do the modelling with 58^{o} joint dip (the most critical orientation) for 60^{o} and 65^{o} footwall slope.

In the first phase an initial grid was formed. Then gravity was applied to the gird points and the gravitational stresses were allowed to equilibrate. Now the desired excavation was done, which was followed by the simulation process.Fig. 4 shows the grid and boundary of the complete slope model with 60^{o} slope angle which is to be used for numerical modelling. Another slope model with 65^{o} slope angle is having same type of grid except the change in slope angle.The models are well extended to nullify the boundary effect.

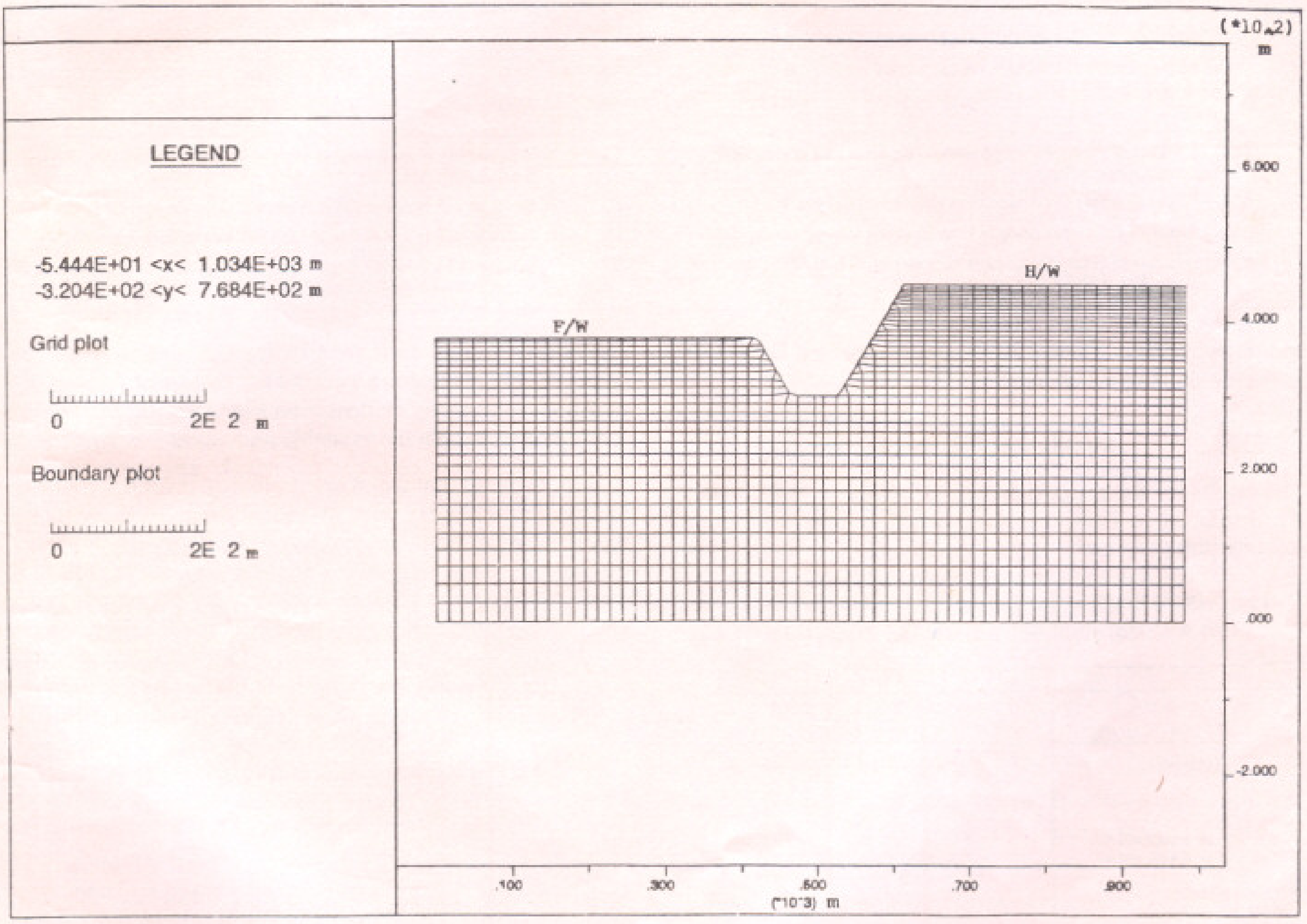

Fig.4. Grid and boundary plot of the complete slope model with 60^{o} slope angle for numerical modelling

Further stability analysis was done by limit equilibrium method to check the result by numerical modelling. Plane failure analysis for overall slope was done by one of the five different available options, "SAPF" computer programme developed by the first author[15]. This option of the programme computes factor of safety under four different conditions in a single run (Table 8). Analysis with 20 m tension crack depth was done because most of the joints of J1 joint set (which may open up to form tension crack) have been traced with persistence of about 20 m.

The applicable condition for the copper open pit can be regarded as "drained slope with tension crack" (i.e. F2 in Tables 8 and 9). Because tension crack can develop along the well developed steeply dipping joint set J1. The mine is located in semi arid region with only about 50 cm/year of rainfall. Quick run-off of the rain water occurs due to hilly topography of the area. So, selection of the slope condition to be "drained slope with tension crack" is justified.

In the same way analysis for footwall slope was also done by SAPF computer programme (Table 9).

The kinematic analysis shows no any critical wedge geometry in hangingwall and foorwall slopes (Fig. 3).

The metabasic dyke (Fig. 1) will not cause any unstable condition because of it's location in the middle part of the pit, which will be mined out. At depth the dyke can form a part of

TABLE 8 - FACTOR OF SAFETY FOR HANGINGWALL SLOPE BY LIMIT EQUILIBRIUM METHOD

Overall slope height = 148 m Friction angle = 35°
Cohesion =0.049 MPa Unit weight =26.28 kN/m^3

Failure plane inclination (°)	Tension crack depth (m)	F1	F2	F3	F4
	60° overall slope				
55	20.0	0.56	0.78	0.79	0.39
58	20.0	0.62	1.26	1.16	0.20
	65° overall slope				
55	20.0	0.52	0.63	0.65	0.44
58	20.0	0.48	0.64	0.65	0.37
63	20.0	0.53	1.15	1.08	0.13

F1 is factor of safety for slope with water up to half of the depth of the tension crack,

F2 factor of safety for drained slope with tension crack,

F3 factor of safety for drained slope without tension crack,

F4 is factor of safety for slope with water up to half of the depth of slope, but without tension crack.

TABLE 9 - FACTOR OF SAFETY FOR FOOTWALL SLOPE BY LIMIT EQUILIBRIUM METHOD

Overall slope height = 77m Friction angle = 33°
Cohesion = 0.051 MPa Unit weight = 25.69 kN/ m^3

Failure plane inclination (°)	Tension crack depth (m)	F1	F2	F3	F4
	60° overall slope				
55	20.0	0.63	1.19	1.07	0.69
58	20.0	1.80	10.10	1.86	0.98
	65° overall slope				
55	20.0	0.53	0.75	0.78	0.58
58	20.0	0.51	0.85	0.85	0.58
60	20.0	0.54	1.07	0.98	0.61

F1 is factor of safety for slope with water up to half of the depth of the tension crack,

F2 factor of safety for drained slope with tension crack,

F3 factor of safety for drained slope without tension crack,

F4 is factor of safety for slope with water up to half of the depth of slope, but without tension crack.

hangingwall slope where it is favourably oriented because it is steeply dipping inside hangingwall.

Result and discussion

The results for the selected part of the complete slope model are displayed in Figs. 5 and 6, which is important from stability point of view.

Fig. 5 is plasticity indicator for 60° footwall and hangingwall slope with 58° joint dip. The plot of plasticity indicator shows a symbol in each zone indicating whether yield has occurred. This plot permit a quick examination of the stability in slopes. It is clearly evident from Fig. 5 that the ubiquitous joints are stable with the available joint shear strength.

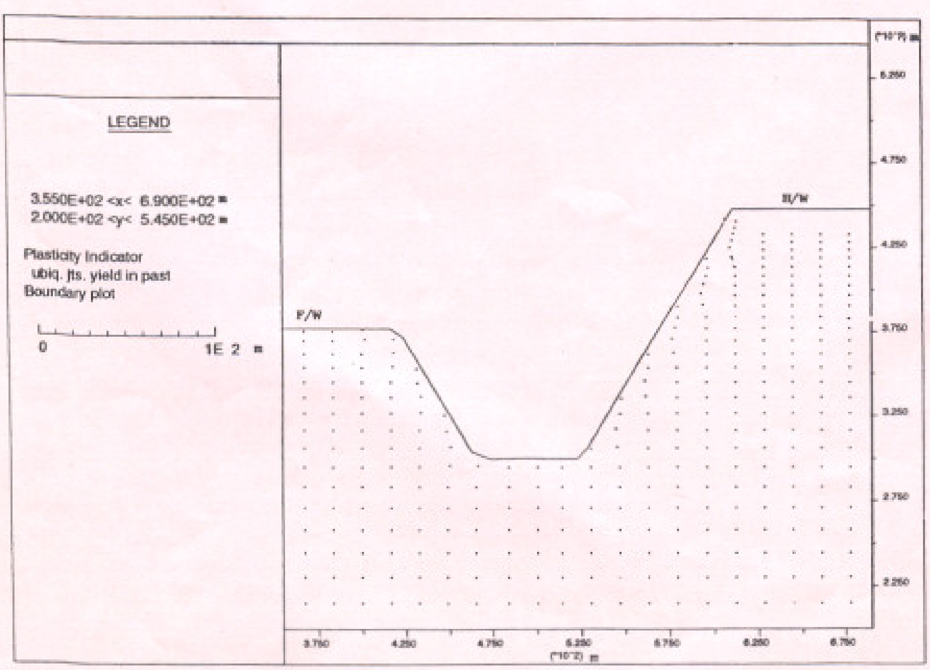

Fig.5. Plasticity indicator of 60° slope with 58° joint dip

Fig. 6 shows that the plasticity indicator for 65° footwall and hangingwall slope with 58° joint dip. Fig. 6 clearly shows that ubiquitous joints are yielding in hangingwall slope, but in footwall slope only two joint elements are yielding. It means 65° hangingwall slope is unstable for 58° dipping joints and the footwall is critically stable. Since, the haul roads are to be located in footwall slope, the critical stability is not acceptable. Hence, 65° slope angle will not be suitable. Therefore 60° pit slope angle for both footwall and hangingwall is the best logical choice.

Further the result of numerical modelling was checked by limit equilibrium method. It is evident from Table 8 that 60° hangingwall slope (drained slope with tension crack, i.e. F2) is stable with failure plane dipping at 58° with the available joint shear strength. It may be recalled that the applicable slope condition for the present case study was already adjudged to be "drained slope with tension crack". The same slope becomes critically stable with 55° joint dip. Hence joints dipping at and less than 55° will be critical for 60° slope angle in hangingwall. It is evident from dip ring analysis of daylighting joints of J1 joint set

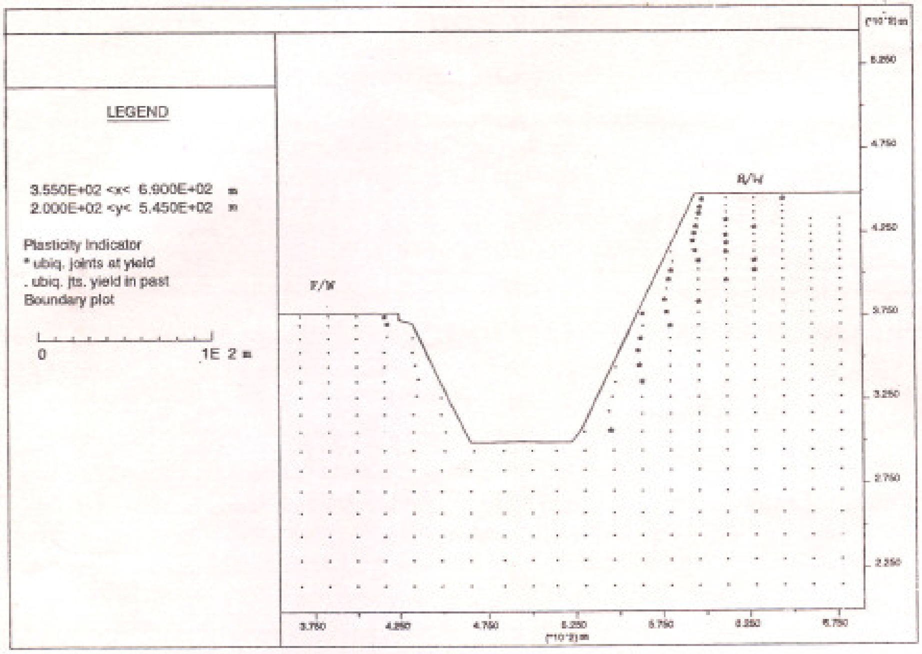

Fig. 6. Plasticity indicator of 65° slope with 85° joint dip.

that total 10 joints, of total 719 mapped, are having dip less than 56° (Table 6). As such these few observations are not representative of the overall structure and also do not come from the same area. At the same time 65° hangingwall slope becomes unstable with 55° and 58° joint inclination both.

It is also clear from Table 9 that 60° footwall slope is stable with the available shear strength along the joints. However, the 65° slope is critically stable with few joints having inclination between 60° and 65°. Hence, 60° footwall slope angle is safe from plane failure conditions.

There is no any critical wedge geometry in 60° slope of hangingwall and footwall slope both (Fig. 3).

Hence, the result of limit equilibrium method shows that 60° overall slope angle for hangingwall and footwall will be the best logical choice.

The same conclusion was also drawn by numerical modelling technique.

It is noteworthy that before this geotechnical study the open pit was designed at 45° overall slope angle. Based on the present geotechnical studies the mine management got the permission from Directorate General of Mines Safety, (DGMS), (the only Federal safety enforcing agency in India) to excavate the open pit with a maximum 60° overall slope angle. It is the steepest slope angle permitted by DGMS for 148 m deep open pit mine in India.

Slope monitoring of 55 observation stations located at the crest and on the benches, was done by electronic distance meter (Wild make D14L model) and precise level (Wild make NA2 model), to determine any movement in and around the open pit. Till date no movement has been observed. At present mining is being done at 120 m depth, from hangingwall side, successfully.

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